

LOW-PASS FILTER, FEEDBACK SYSTEM, AND SEMICONDUCTOR INTEGRATED CIRCUIT

BACKGROUND OF THE INVENTION

5 The present invention relates to a low-pass filter and specifically to a technique of a low-pass filter suitable for use as a loop filter in a feedback system, such as a phase locked loop circuit, a delay locked loop, or the like.

 In currently-existing semiconductor integrated circuit systems, a feedback system, especially a phase locked loop circuit (hereinafter, referred to as "PLL"), is one of
10 the indispensable components and is incorporated in almost all the LSI devices. The applications of the feedback system range over various technological fields, such as communication devices, microprocessors, IC cards, etc.

 FIG. 13 shows the structure of a general charge pump type PLL. General features of the PLL are described with reference to FIG. 13. A phase comparator 10
15 compares input clock CK_{in} which is supplied to the PLL and feed back clock CK_{div} and outputs up signal UP and down signal DN according to the phase difference between the compared clocks. A charge pump circuit 20 outputs (releases or sucks) electric current I_p based on up signal UP and down signal DN. A loop filter 30 smoothes electric current I_p and outputs voltage V_{out} as a result of the smoothing of electric current I_p. A voltage
20 controlled oscillator 40 changes the frequency of output clock CK_{out} of the PLL based on voltage V_{out}. A frequency divider 50 divides output clock CK_{out} by N, and a resultant clock is fed back as feedback clock CK_{div} to the phase comparator 10. By repeating the above operation, output clock CK_{out} gradually converges on a predetermined frequency and is locked.

25 The loop filter 30 is an especially significant component among the above

components of the PLL. It can be said that the response characteristic of the PLL is determined according to the filter characteristics of the loop filter 30.

FIGS. 14A and 14B show general loop filters. FIG. 14A shows a passive filter. FIG. 14B shows an active filter. These filters are equivalently replaceable with each other and have the same transfer characteristic. As seen from FIGS. 14A and 14B, the loop filter 30 is substantially a low-pass filter formed by a combination of a resistive element and a capacitive element irrespective of whether it is a passive filter or an active filter.

According to the control theory for PLLs, the response bandwidth of the PLL is preferably about a 1/10 of the frequency of the input clock at the maximum. If this theory is followed, in a PLL which receives a reference clock having a relatively low frequency, it is necessary to reduce the cutoff frequency of the loop filter such that the response bandwidth is narrowed. Thus, a loop filter in a conventional PLL has a relatively large time constant, i.e., a large CR product. In general, a larger capacitive element is used in order to achieve a larger CR product.

However, increasing the size of the capacitive element causes an increase in the circuit size. This is a serious problem especially in a semiconductor integrated circuit including a large number of PLLs, such as a microprocessor, or the like. Further, especially in an IC card, it should be avoided, in view of reliability, to incorporate an element thicker than the card. The countermeasure of externally providing a large capacitive element is substantially impossible. Conventionally, the following means have been provided for the purpose of decreasing the size of the capacitive element of the loop filter.

In the first countermeasure example, a loop filter is structured such that a capacitive element and a resistive element, which would generally be connected in series,

are separated, and separate electric currents are supplied to these elements. The voltages generated in the elements are added together in an adder circuit, and a resultant voltage is output from the adder circuit (see, for example, the specification of Japanese Patent No. 2778421 (page 3 and FIG. 1)). According to this loop filter, the electric current
5 supplied to the capacitive element is smaller than that supplied to the resistive element, whereby the filter characteristics equivalent to those of a conventional filter are maintained, and the size of the capacitive element is relatively decreased.

The second countermeasure example is a low-pass filter disclosed in a patent application in which the present inventors are concerned (WO 03/098807 A1). In
10 this low-pass filter, a filtering process of an input signal is performed by first filter means, and a filtering process of a second electric current generated based on first electric current flowing through the first filter means is performed by second filter means. Further, the first and second voltages generated in the first and second filter means, respectively, are added together by adder means and a resultant voltage is output from the low-pass filter.
15 In this circuit, the second electric current is generated so as to be smaller than the first electric current, whereby the size of a capacitive element of the second filter means is relatively decreased while the filter characteristics equivalent to those of a conventional low-pass filter are maintained.

In the above first and second examples, the objective of reducing the size of
20 the capacitive element is achieved, but on the other hand, collateral problems emerge. For example, in the first example, it is necessary to provide an adder circuit even when a passive loop filter is constructed, and accordingly, the circuit area and circuit complexity are increased. The second example is originally directed to an active loop filter and therefore basically includes an operational amplifier. Therefore, the second example does
25 not require an additional addition means that is required in the first example. A problem in

the second example is that the resistance value of a resistive element in electric current generation means which generates the second electric current is increased although the second electric current is decreased and the size of the capacitive element in the second filter means is decreased. The increase of the resistance value undesirably causes a
5 deterioration in the noise characteristics because the resistor generates thermal noise.

SUMMARY OF THE INVENTION

In view of the above problems, an objective of the present invention is to achieve a low-pass filter having filter characteristics equivalent to those of a conventional
10 low-pass filter without causing collateral problems, such as an increase in the circuit area, the circuit complexity, or the resistance value, which may be caused due to size reduction of a capacitive element in the conventional low-pass filter. Another objective of the present invention is to provide a feedback system including such a low-pass filter of the present invention as a loop filter and a semiconductor integrated circuit including such a
15 feedback system.

A measure taken by the present invention for achieving the above objectives is a low-pass filter comprising: a first element block having a capacitive element; a second element block having a resistive element, the second element block being connected in series to the first element block; a first input terminal for receiving a first electric current,
20 the first input terminal being provided at the side including any one of the first and second element blocks; and a second input terminal for receiving a second electric current, the second input terminal being connected to a connection point of the first element block and the second element block, wherein the total voltage generated in the first and second element blocks is employed as an output signal. The first element block receives at least a
25 part of the first electric current which corresponds to a difference between the electric

current flowing through the second element block and the second electric current.

With this structure, the electric current flowing through the first element block is smaller than the electric current flowing through the second element block. In the case where the electric current flows from the first element block to the second element block, the second electric current which is received at the second input terminal is merged into the electric current flowing through the first element block, and the resultant electric current flows through the second element block. In the case where the electric current flows from the second element block to the first element block, the electric current flowing through the second element block is divided and supplied to the second input terminal as the second electric current. Therefore, only the size of the capacitive element of the first element block is relatively decreased without increasing the resistance value of a resistive element in the second element block, whereby the voltage generated in the first and second element blocks is maintained. Thus, the size of the capacitive element in the low-pass filter is decreased without causing collateral problems, such as an increase in the resistance value or the circuit complexity, or the like.

Specifically, in the above-described low-pass filter, the first input terminal is provided at the side including the second element block; and the second electric current is an electric current whose direction is opposite to that of the first electric current and whose magnitude is N times that of the first electric current (where N is a predetermined number).

Specifically, in the above-described low-pass filter, the first input terminal is provided at the side including the first element block; and the second electric current is an electric current whose direction is the same as that of the first electric current and whose magnitude is N times that of the first electric current (where N is a predetermined number).

Preferably, the above-described low-pass filter further comprises a third

element block which has a capacitive element and is provided between the first input terminal and a reference voltage. With this structure, a secondary low-pass filter can be constructed.

Preferably, the above-described low-pass filter further comprises an
5 operational amplifier which has a normal phase input terminal, an inverted phase input terminal, and an output terminal, wherein: the first and second element blocks are provided between the inverted phase input terminal and the output terminal of the operational amplifier, and the normal phase input terminal of the operational amplifier is supplied with a reference voltage; and the first input terminal is provided at the side including the
10 inverted phase input terminal of the operational amplifier. With this structure, an active low-pass filter can be constructed.

A variation of the above-described low-pass filter is a low-pass filter comprising: a first element block having a capacitive element; a second element block having a resistive element, the second element block being connected in series to the first
15 element block; an operational amplifier having a normal phase input terminal, an inverted phase input terminal, and an output terminal, the first and second element blocks being provided between the inverted phase input terminal and the output terminal, the normal phase input terminal being supplied with a reference voltage; a first input terminal for receiving a first electric current; a second input terminal for receiving a second electric
20 current, the second input terminal being connected to the inverted phase input terminal of the operational amplifier; and a third element block having a capacitive element and a resistive element, the capacitive element being provided between the first input terminal and the reference voltage, the resistive element being provided between the first input terminal and the inverted phase input terminal of the operational amplifier, wherein the
25 total voltage generated in the first and second element blocks is employed as an output

signal. The first element block receives at least a part of the first electric current which corresponds to a difference between the electric current flowing through the resistive element of the third element block and the second electric current.

In this low-pass filter, the second input terminal is provided not between the
5 first element block and the second element block but between the first and second element blocks and the third element block. With this structure, the electric current flowing through the first element block is smaller than the electric current flowing through the resistive element of the third element block. In the case of this low-pass filter, the resistance value of the resistive element in the second element block increases, but the size
10 of the capacitive element in the first element block decreases.

Another measure taken by the present invention for achieving the above objectives is a feedback system for feeding back an output clock generated based on an input clock such that the output clock has a predetermined characteristic, comprising: a loop filter including a first element block which has a capacitive element, a second element
15 block which has a resistive element and is connected in series to the first element block, a first input terminal for receiving a first electric current which is provided at the side including any one of the first and second element blocks, and a second input terminal for receiving a second electric current, which is connected to a connection point of the first and second element blocks, the first element block receiving at least a part of the first
20 electric current which corresponds to a difference between the electric current flowing through the second element block and the second electric current, the total voltage generated in the first and second element blocks being employed as an output signal; a charge pump circuit for generating the first and second electric currents based on a phase difference between the input clock and the fed-back clock; and output clock generation
25 means for generating the output clock based on the output signal from the loop filter.

In this way, a filter having the same structure as that described above is used as a loop filter in a feedback system, whereby the circuit area of the entire feedback system is reduced.

Specifically, the output clock generation means is a voltage controlled oscillator which oscillates the output clock and changes the oscillation frequency based on the output signal from the loop filter.

Specifically, the output clock generation means is a voltage controlled delay circuit which changes a delay amount of the output clock with respect to the input clock based on the input clock and the output signal from the loop filter.

Specifically, in the above-described feedback system, the first input terminal of the loop filter is provided at the side including the second element block. The direction of the second electric current is opposite to that of the first electric current, and the magnitude of the second electric current is N times that of the first electric current (where N is a predetermined number). The charge pump circuit includes a first partial charge pump circuit which outputs/receives the first electric current and a second partial charge pump circuit which outputs/receives the second electric current.

Specifically, in the above-described feedback system, the first input terminal of the loop filter is provided at the side including the second element block. The direction of the second electric current is opposite to that of the first electric current, and the magnitude of the second electric current is N times that of the first electric current (where N is a predetermined number). The charge pump circuit includes a first partial charge pump circuit which outputs/receives an electric current corresponding to a difference between the first electric current and the second electric current and a second partial charge pump circuit which outputs/receives the second electric current, the charge pump circuit combining the electric currents output from/received by the first and second

partial charge pump circuits to obtain the first electric current.

Specifically, in the above-described feedback system, the first input terminal of the loop filter is provided at the side including the first element block. The direction of the second electric current is the same as that of the first electric current, and the magnitude of the second electric current is N times that of the first electric current (where N is a predetermined number). The charge pump circuit includes a first partial charge pump circuit which outputs/receives the first electric current and a second partial charge pump circuit which outputs/receives the second electric current.

10

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows the structure of a feedback system according to embodiment 1 of the present invention.

FIGS. 2A-2C show circuit diagrams of a general passive filter and low-pass filters according to embodiment 1 of the present invention.

15

FIG. 3 shows the structure of a feedback system according to embodiment 2 of the present invention.

FIGS. 4A-4C show circuit diagrams of a general active filter and low-pass filters according to embodiment 2 of the present invention.

20

FIG. 5 is a circuit diagram of a charge pump circuit provided in the feedback systems according to embodiments 1 and 2 of the present invention.

FIG. 6 shows the structure of a feedback system according to embodiment 3 of the present invention.

FIGS. 7A-7C show circuit diagrams of a general passive filter and low-pass filters according to embodiment 3 of the present invention.

25

FIG. 8 is a circuit diagram of an active filter which is applicable to the

feedback system of embodiment 3 of the present invention.

FIG. 9 shows an application of a feedback system of the present invention to an IC card.

FIG. 10 shows an application of a feedback system of the present invention to a COC component.

FIG. 11 shows an example of installation of a feedback system of the present invention in an LSI pad region.

FIG. 12 shows an example of installation of a feedback system of the present invention in a microprocessor.

FIG. 13 shows the structure of a general charge pump PLL.

FIGS. 14A and 14B are circuit diagrams of a general loop filter.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Hereinafter, embodiments of the present invention are described with reference to the drawings.

(Embodiment 1)

FIG. 1 shows the structure of a feedback system according to embodiment 1 of the present invention. The feedback system of embodiment 1 is a PLL including a phase comparator 10, a charge pump circuit 20A, a loop filter 30A, a voltage controlled oscillator (output clock generation means) 40, and a frequency divider 50. Among these components, the phase comparator 10, the voltage controlled oscillator 40, and the frequency divider 50 are as described above. Hereinafter, the charge pump circuit 20A and the loop filter 30A are described in detail.

The charge pump circuit 20A includes two general charge pump circuits

(partial charge pump circuits) **20a** and **20b**. The charge pump circuit **20a** outputs/receives electric current I_p according to signal UP and signal DN which are output from the phase comparator **10**. The charge pump circuit **20b** outputs/receives electric current αI_p according to signal UP and signal DN. The direction of electric current αI_p is opposite to
5 that of electric current I_p . The magnitude of electric current αI_p is α times that of electric current I_p ($0 < \alpha < 1$). That is, the charge pump circuit **20A** outputs/receives two lines of electric currents, electric current I_p and opposite electric current αI_p , according to signal UP and signal DN.

Electric currents I_p and αI_p output from/input to the charge pump
10 circuit **20A** are input to the loop filter **30A** at input terminals IN1 and IN2, respectively. In the loop filter **30A**, a capacitive element (first element block) **31** is provided between input terminal IN2 and a reference voltage. Further, a resistive element **32** and a capacitive element **33**, which are connected in parallel and constitute the second element block, are provided between input terminal IN1 and input terminal IN2. The loop filter **30A** outputs
15 voltage V_{out} of input terminal IN1, i.e., a total voltage generated in the capacitive element **31** and the resistive element **32**.

In the loop filter **30A**, electric current I_p supplied at input terminal IN1 flows through the resistive element **32** and the capacitive element **33** which are connected in parallel. Electric current αI_p , which is a part of electric current I_p , is extracted from
20 input terminal IN2. Thus, only a part of the electric current flowing through the resistive element **32** and the capacitive element **33**, which are connected in parallel, is allowed to flow through the capacitive element **31**. Accordingly, the static capacitance of the capacitive element **31** may be relatively decreased. The total voltage generated in a downsized version of the capacitive element **31** and the resistive element **32** is equal to the
25 voltage generated when electric current I_p is supplied at input terminal IN1 in the structure

where input terminal IN2 is not provided, and the size of the capacitive element 31 is not decreased.

FIG. 2 shows the circuit structures of a general passive filter and low-pass filters according to embodiment 1. A loop filter 30 shown in part (a) of FIG. 2 is a general low-pass filter having a transfer characteristic equivalent to that of the loop filter 30 shown in FIG. 14A. Herein, input terminal IN2 is provided between the capacitive element 31 and the resistive element 32. Electric current $9I_p/10$ is supplied to input terminal IN2 in the direction opposite to that of electric current I_p that is supplied to input terminal IN1. The static capacitance of the capacitive element 31 is multiplied by $1/10$. As a result, the low-pass filter shown in part (b) of FIG. 2, i.e., the loop filter 30A of embodiment 1, is obtained. The loop filter 30 shown in part (a) of FIG. 2 and the loop filter 30A shown in part (b) of FIG. 2 have the same transfer function which is expressed by the following expression:

$$1+(C_3R+RC)s/(s(1+sC_3R)C) \quad \text{..... (1)}$$

As described above, the loop filter 30A of embodiment 1 has a transfer characteristic equivalent to that of the general passive loop filter 30, but the static capacitance of the capacitive element 31 in the loop filter 30A is smaller than in the conventional loop filter 30. The reduction in the static capacitance of the capacitive element 31 does not require an increase in the resistance value of the resistive element 32 as compensation. Further, it is not necessary to additionally provide an adder circuit for adding together the voltage generated in the capacitive element 31 and the voltage generated in the resistive element 32. That is, a passive loop filter having a greatly reduced size as compared with the conventional passive loop filter 30 is realized only by providing input terminal IN2 and supplying a predetermined electric current thereto without making any modification to the circuit structure of the conventional passive loop filter 30.

The loop filter 30A can be equivalently converted to a loop filter 30B shown in part (c) of FIG. 2 by adjusting respective element values so as to satisfy the following condition:

$$(1+C_3/C)/(RC_3)=(1+10C_4/C)/(R_2C_4) \quad \dots (2)$$

5 The loop filter 30B includes a capacitive element (first element block) 31, a resistive element (second element block) 32 which is connected in series to the capacitive element 31, and a capacitive element (third element block) 33 which is connected to input terminal IN1. One end of the capacitive element 33 is connected to the reference voltage. The circuit structure of the loop filter 30B is substantially the same as that of the
10 conventional passive filter shown in FIG. 14A. In FIG. 1, as a matter of course, the loop filter 30A may be replaced with the loop filter 30B.

As described above, according to embodiment 1, a loop filter having a transfer characteristic equivalent to that of a conventional passive loop filter is realized only by decreasing the static capacitance of a capacitive element without making any
15 substantial modification to the circuit structure of the conventional passive loop filter and without increasing the resistance value of a resistive element in the loop filter.

In the example described above, the static capacitance of the capacitive element 31 is multiplied by 1/10, but the present invention is not limited thereto. For example, electric current 99Ip/100 may be supplied to input terminal IN2, whereby the
20 static capacitance of the capacitive element 31 is reduced to a 1/100. It is apparent that the static capacitance of the capacitive element 31 is further reduced.

(Embodiment 2)

FIG. 3 shows the structure of a feedback system according to embodiment 2
25 of the present invention. The feedback system of embodiment 2 is a PLL including an

active loop filter 30C, whereas the feedback system of embodiment 1 is a PLL including the passive loop filter 30A. The components of the PLL of embodiment 2 are as described in embodiment 1 except for the loop filter 30C. Hereinafter, the loop filter 30C is described in detail.

5 The loop filter 30C includes a capacitive element (first element block) 31, a resistive element (second element block) 32 connected in series to the capacitive element 31, a capacitive element (third element block) 33, a resistive element 34, and an operational amplifier 35. The output terminal of the operational amplifier 35 is connected to one end of the capacitive element 31. The inverted phase input terminal of the
10 operational amplifier 35 is connected to a connection point of the resistive element 32 and the resistive element 34. The normal phase input terminal of the operational amplifier 35 is supplied with a reference voltage. In the loop filter 30C, input terminal IN1 is connected to a connection point of the capacitive element 33 and the resistive element 34, and input
15 terminal IN2 is connected to a connection point of the capacitive element 31 and the resistive element 34. The loop filter 30C receives electric current I_p and electric current αI_p output from/input to the charge pump circuit 20A at input terminals IN1 and IN2, respectively. The loop filter 30C outputs voltage V_{out} of the output terminal of the operational amplifier 35, i.e., the total voltage generated in the capacitive element 31 and the resistive element 32.

20 In the loop filter 30C, a part of electric current I_p which is supplied at input terminal IN1 flows through the resistive element 32, and electric current αI_p , which is a part of the electric current passed through the resistive element 32, is extracted through input terminal IN2. Thus, only a part of the electric current passed through the resistive element 32 flows into the capacitive element 31, and therefore, the static capacitance of the
25 capacitive element 31 can be relatively decreased. The voltage obtained at the output

terminal of the operational amplifier 35 in the case of a downsized version of the capacitive element 31 is equal to the voltage generated when electric current I_p is supplied at input terminal IN1 in the structure where input terminal IN2 is not provided, and the size of the capacitive element 31 is not decreased.

5 FIG. 4 shows circuit structures of a general active filter and low-pass filters according to embodiment 2 of the present invention. The loop filter 30 shown in part (a) of FIG. 4 is the same as the loop filter 30 shown in FIG. 14B. Herein, input terminal IN2 is provided between the capacitive element 31 and the resistive element 32. Electric current $9I_p/10$ is supplied at input terminal IN2 in the direction opposite to that of electric
10 current I_p supplied at input terminal IN1, and the static capacitance of the capacitive element 31 is multiplied by $1/10$, whereby a low-pass filter shown in part (b) of FIG. 4, i.e., the loop filter 30C of embodiment 2, is obtained. The loop filter 30 shown in part (a) of FIG. 4 and the loop filter 30C shown in part (b) of FIG. 4 have the same transfer function which is substantially expressed by expression (1).

15 As described above, the loop filter 30C of embodiment 2 has a transfer characteristic equivalent to that of the general active loop filter 30, but the static capacitance of the capacitive element 31 in the loop filter 30C is smaller than in the conventional loop filter 30. The reduction in the static capacitance of the capacitive element 31 does not require an increase in the resistance value of the resistive element 32
20 as compensation. That is, a loop filter having a greatly reduced size as compared with the conventional passive loop filter 30 is realized only by providing input terminal IN2 and supplying a predetermined electric current thereto without making any modification to the circuit structure of the conventional passive loop filter 30.

 The loop filter 30C can be equivalently converted to the loop filter 30D
25 shown in part (c) of FIG. 4. The loop filter 30D is different from the loop filter 30C in that

input terminal IN2 is connected to the inverted phase input terminal of the operational amplifier 35, i.e., connected to a connection point of the resistive element 32 and the resistive element 34. Also in the loop filter 30D, the electric current flowing into the capacitive element 31 is decreased, and accordingly, the static capacitance of the capacitive element 31 is relatively decreased. However, the electric current flowing through the resistive element 32 is also decreased, and therefore, the resistance value of the resistive element 32 is set to a relatively large value. In FIG. 3, the loop filter 30C may be replaced with the loop filter 30D.

As described above, according to embodiment 2, a loop filter having a transfer characteristic equivalent to that of a conventional active loop filter is realized only by decreasing the static capacitance of a capacitive element without making any substantial modification to the circuit structure of the conventional active loop filter and, in some cases, without increasing the resistance value of a resistive element in the loop filter.

Also in embodiment 2, the static capacitance of the capacitive element 31 may be reduced to a 1/100 by supplying, for example, electric current $99I_p/100$ to input terminal IN2. It is apparent that the static capacitance of the capacitive element 31 may further be reduced.

In embodiments 1 and 2, the charge pump circuit 20A includes two general charge pump circuits 20a and 20b. The charge pump circuits 20a and 20b respectively output/receive electric currents I_p and αI_p which have opposite polarities. Thus, in one of the charge pump circuits 20a and 20b, the electric current source for charge and the electric current source for discharge do not operate simultaneously. Therefore, the charge pump circuit 20A can be replaced with the charge pump circuit 20B shown in FIG. 5.

The charge pump circuit 20B includes electric current sources 21, 22, 23 and 24. However, among these sources, the electric current sources 21 and 23 merely

resulted from dividing a conventional current source which supplies electric current I_p such that supplied electric currents have a ratio of $\alpha:(1-\alpha)$. This also applies to the electric current sources **22** and **24**. When signal UP is supplied, control switches **SW1**, **SW3** and **SW5** are brought into conduction, so that electric current I_p , which is the sum of the electric currents supplied from the electric current sources **21** and **23**, is released from the charge pump circuit **20B**, and electric current αI_p is sucked into the charge pump circuit **20B**. On the other hand, when signal DN is supplied, control switches **SW2**, **SW4** and **SW6** are brought into conduction, so that electric current I_p , which is the sum of the electric currents supplied from the electric current sources **22** and **24**, is sucked into the charge pump circuit **20B**, and electric current αI_p is released from the charge pump circuit **20B**. Thus, in the case where the charge pump circuit **20B** is included in the PLL of embodiment 1 or 2, the PLL has substantially the same circuit structure as that of a conventional PLL, but only the size of a capacitive element of the loop filter is decreased.

(Embodiment 3)

FIG. 6 shows the structure of a feedback system according to embodiment 3 of the present invention. The feedback system of embodiment 3 is a delay locked loop circuit (hereinafter, referred to as “DLL”) including a phase comparator **10**, a charge pump circuit **20C**, a loop filter **30E**, and a voltage controlled delay circuit (output clock generation means) **40**. Hereinafter, the charge pump circuit **20C** and the loop filter **30E** are described in detail.

The charge pump circuit **20C** includes current sources **21** and **23** for charge, which supply electric currents αI_p and $(1-\alpha)I_p$, respectively, and current sources **22** and **24** for discharge as does the above-described charge pump circuit **20B**. When signal UP is supplied, control switches **SW1** and **SW3** are brought into conduction so that electric

currents αI_p and $(1-\alpha)I_p$ are released. On the other hand, when signal DN is supplied, control switches SW2 and SW4 are brought into conduction so that electric currents αI_p and $(1-\alpha)I_p$ are sucked. That is, two lines of electric currents, which are obtained by interiorly dividing electric current I_p with the ratio of $\alpha:(1-\alpha)$, are output from/input to the
5 charge pump circuit 20C.

Electric currents αI_p and $(1-\alpha)I_p$ output from/input to the charge pump circuit 20C are input to the loop filter 30E at input terminals IN1 and IN2, respectively. In the loop filter 30E, a capacitive element (first element block) 31 is provided between input terminal IN1 and input terminal IN2. Further, between input terminal IN2 and a reference
10 voltage, there are a resistive element 32 and a capacitive element 33, which are connected in parallel and constitute the second element block. The loop filter 30E outputs voltage V_{out} of input terminal IN1, i.e., a total voltage generated in the capacitive element 31 and the resistive element 32.

In the loop filter 30E, electric current αI_p supplied at input terminal IN1
15 flows through the capacitive element 31, and the resistive element 32 and the capacitive element 33 which are connected in parallel. Electric current $(1-\alpha)I_p$ is supplied to input terminal IN2 in the same direction as that of electric current αI_p and flows through the resistive element 32 and the capacitive element 33 which are connected in parallel. Thus, only a part of the electric current flowing through the resistive element 32 and the
20 capacitive element 33, which are connected in parallel, is allowed to flow through the capacitive element 31. Accordingly, the static capacitance of the capacitive element 31 may be relatively decreased. The total voltage generated in a downsized version of the capacitive element 31 and the resistive element 32 is equal to the voltage generated when electric current I_p is supplied at input terminal IN1 in the structure where input
25 terminal IN2 is not provided, and the size of the capacitive element 31 is not decreased.

FIG. 7 shows circuit structures of a general passive filter and low-pass filters according to embodiment 3 of the present invention. The loop filter 30 shown in part (a) of FIG. 7 is a general low-pass filter having a transfer characteristic equivalent to that of the loop filter 30 shown in FIG. 14A. Herein, the electric current supplied to input terminal IN1 and the static capacitance of the capacitive element 31 are multiplied by 1/10. Input terminal IN2 is provided between the capacitive element 31 and the resistive element 32. Electric current $9I_p/10$ is supplied at input terminal IN2 in the same direction as that of electric current $I_p/10$ supplied at input terminal IN1. As a result, a low-pass filter shown in part (b) of FIG. 7, i.e., the loop filter 30E of embodiment 3, is obtained. The loop filter 30 shown in part (a) of FIG. 7 and the loop filter 30E shown in part (b) of FIG. 7 have the same transfer function which is substantially expressed by expression (1).

As described above, the loop filter 30E of embodiment 3 has a transfer characteristic equivalent to that of the general passive loop filter 30, but the static capacitance of the capacitive element 31 in the loop filter 30E is smaller than in the conventional loop filter 30. The reduction in the static capacitance of the capacitive element 31 does not require an increase in the resistance value of the resistive element 32 as compensation. Further, it is not necessary to additionally provide an adder circuit for adding together the voltage generated in the capacitive element 31 and the voltage generated in the resistive element 32. Furthermore, the circuit size of the charge pump circuit 20C does not increase as compared with a conventional one. That is, a loop filter and PLL, which have greatly reduced sizes as compared with the conventional passive loop filter 30 and PLL, is realized only by providing input terminal IN2 and supplying a predetermined electric current thereto without making any modification to the circuit structures of the conventional passive loop filter 30 and PLL.

The loop filter 30E can be equivalently converted to a loop filter 30F shown

in part (c) of FIG. 7 by adjusting respective element values so as to satisfy the condition of expression (2). The loop filter 30F includes a capacitive element (first element block) 31, a resistive element (second element block) 32 which is connected in series to the capacitive element 31, and a capacitive element (third element block) 33 which is connected to input terminal IN1. One end of the capacitive element 33 is connected to the reference voltage. Thus, the circuit structure of the loop filter 30F is substantially the same as that of the conventional passive filter shown in FIG. 14A. In FIG. 6, as a matter of course, the loop filter 30E may be replaced with the loop filter 30F.

Alternatively, the loop filter 30E in FIG. 6 may be replaced with an active loop filter 30G shown in FIG. 8. The loop filter 30G is obtained by modifying the loop filter 30C shown in part (b) of FIG. 4 such that the capacitive element 31 and the resistive element 32 are replaced with each other, the direction of the electric current supplied to input terminal IN2 is inverted, the electric current supplied to input terminal IN1 and the static capacitance of the capacitive element 33 are each multiplied by 1/10, and the resistance value of the resistive element 34 is multiplied by 10. Thus, the loop filter 30C and the loop filter 30G have the same transfer characteristic.

In the loop filter 30G, the static capacitance of the capacitive element 33 is decreased, but accordingly, the size of the resistive element 34 is increased. The electric current flowing into the operational amplifier 35 is relatively large as compared with the loop filter 30C. However, considering the decrease in size of the capacitive element 31, the loop filter 30G is capable of sufficiently achieving such an objective.

As described above, according to embodiment 3, a loop filter having a transfer characteristic equivalent to that of a conventional loop filter is realized only by decreasing the static capacitance of a capacitive element without making any substantial modification to the circuit structure of the conventional loop filter. Further, it is not

necessary to substantially change the circuit structure of a charge pump circuit in a conventional feedback system. That is, only the size of the capacitive element in the loop filter can be decreased without making any substantial modification to the entire circuit structure of the conventional feedback system.

5 Also in embodiment 3, the static capacitance of the capacitive element 31 may be reduced to a $1/100$ by supplying, for example, electric currents $I_p/100$ and $99I_p/100$ to input terminals IN1 and IN2, respectively. It is apparent that the static capacitance of the capacitive element 31 may further be reduced.

10 In embodiment 3, a DLL is constructed as the feedback system, but the present invention is not limited thereto. For example, a PLL may be constructed using the above-described charge pump circuit 20C, loop filter 30E, or the like. Conversely, the charge pump circuit 20A and the loop filter 30A of embodiments 1 and 2, or the like, may be used to construct a DLL.

15 As a matter of course, a low-pass filter of the present invention is also usable for applications other than a loop filter in a feedback system.

(Applications of the feedback system of the present invention)

20 As described above, the feedback system of the present invention does not require a large capacitive element, and therefore, the circuit size thereof is reduced. Thus, applications to the products described below are especially expected.

FIG. 9 is an example of an LSI device for an IC card, which incorporates a PLL or DLL of the present invention. An LSI device used for IC cards has a limited installation area, and therefore, the PLL or DLL of the present invention which can be structured with a smaller circuit area is especially suitable for use in an IC card.

25 FIG. 10 shows an application of the PLL or DLL of the present invention to

a chip-on-chip (COC) component. In a chip-on-chip structure, the circuit area of a semiconductor integrated circuit of the upper layer is limited, and therefore, the PLL or DLL of the present invention is effective in such a case.

FIG. 11 shows an application of the PLL or DLL of the present invention to an LSI pad region. The circuit area available for installation is also limited as described above as to the chip-on-chip structure. Therefore, the PLL or DLL of the present invention is accordingly effective in such a case.

FIG. 12 is an example of the PLLs or DLLs of the present invention which are installed as clock generation means in a microprocessor. In currently-existing microprocessors, a large number of PLLs or DLLs are incorporated. Therefore, using the PLLs or DLLs of the present invention in a microprocessor raises the expectation that the entire circuit area of the microprocessor is greatly reduced. Thus, the effects obtained by applying the PLLs or DLLs of the present invention to a microprocessor are significantly large.

As described above, according to the present invention, the size of a capacitive element in a low-pass filter is decreased without any compensation, such as an increase in the circuit area, the circuit complexity, or the resistance value. A low-pass filter of the present invention is used as a loop filter, whereby a feedback system having a greatly decreased size as compared with a conventional loop filter is realized.

The circuit structures of a low-pass filter and a feedback system of the present invention are quite simple and therefore can readily be implemented. Further, according to the present invention, the circuit structures are substantially the same as conventional circuit structures. Therefore, the present invention is advantageous in that the accumulated designing methodologies can be inherited as they are.